Anisotropy and Alfvénicity of hourly fluctuations in the fast polar solar wind

M. Neugebauer[1]
Lunar and Planetary Laboratory, University of Arizona, Tucson, Arizona, USA

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[1] Ulysses magnetic and plasma data obtained in the fast polar solar wind are used to study the nature of fluctuations in the frequency range between the turbulent inertial range and the lower-frequency range dominated by quasi-static structures originating at the Sun. For daily variations of hourly averages of the magnetic field components the anisotropy of the fluctuations is less than in the higher-frequency range, and the minimum variance direction loses its alignment with the magnetic field in favor of a more radial direction as the solar distance increases. The anisotropy of the magnetic fluctuations also increases with solar distance, while the Alfvénicity, as measured by the correlation of the field and velocity components, decreases. Most of the observed frequency and distance trends are similar to those observed in fast solar wind streams in the ecliptic, despite the difference in stream structure between high and low latitudes. One major difference from higher-frequency (inertial range) variations at high latitudes is the continuing decline of the correlation between velocity and field vectors between 2 and 4.5 AU. It is suggested that the relative contribution of discontinuities and planar magnetic structures grows with solar distance relative to the contribution of Alfvén waves. *INDEX TERMS:* 2149 Interplanetary Physics: MHD waves and turbulence; 2109 Interplanetary Physics: Discontinuities; 2164 Interplanetary Physics: Solar wind plasma; 2134 Interplanetary Physics: Interplanetary magnetic fields; *KEYWORDS:* solar wind, Alfvén waves, anisotropy, Ulysses

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1. Introduction

[2] The high-latitude solar wind encountered by the Ulysses spacecraft during periods of minimum solar activity in 1993–1996 provides a good laboratory for studying the evolution of magnetohydrodynamic (MHD) fluctuations largely free of temporal disturbances and stream interactions. Much of the work on waves and turbulence based on that data set has been reviewed by *Horbury and Tsurutani* [2001]. The properties of the fluctuations in the polar heliospheric field depend on their frequency. Fluctuations with periods shorter than ~1 hour are consistent with MHD turbulence in which energy cascades downward in scale size until the waves are absorbed by wave-particle interactions. At the other extreme of very long periods or large scales, magnetic variations are dominated by quasi-static structures originating at the Sun [*Jokipii and Kóta*, 1989; *Jokipii et al.*, 1995].

[3] The focus of this paper is on fluctuations between those two scales. Outward propagating Alfvén waves are a prominent part of the magnetic spectrum in this range [*Smith et al.*, 1995]. Some analyses, however, conflict with an Alfvén wave interpretation. Alfvén waves would be expected to propagate along the direction of the magnetic field, whereas *Smith et al.* [1997] and *Horbury and Balogh* [2001] find a tendency toward propagation in the solar radial direction rather than along the field. The present study is an attempt to determine the frequency and the radial dependences of the anisotropy, the propagation direction, and the Alfvénicity of magnetic fluctuations in the fast polar solar wind. The final section provides both a summary of the findings of the investigation and a comparison to the results of similar studies in the ecliptic plane.

2. Method

[4] The analysis is based on 1-min, 8-min, and 1-hour averages of the radial, tangential, and normal (RTN) components of the magnetic field measured by the Ulysses helium vector magnetometer described by *Balogh et al.* [1992]. Hourly averages of the vector proton velocity measured by the Ulysses SWOOPS instrument [*Bame et al.*, 1992] are also used.

[5] The study is based on principal-axis [*Sonnerup and Cahill*, 1967] and correlation analyses over intervals of either 1 hour (for the 1-min vectors), 8 hours (for the 8-min data), or 1 day (for the hourly data). The 1-min data over hourly intervals is clearly within the inertial turbulence range. The use of 8-min averages over intervals of 8 hours was selected to bridge the large gap between the use

[1]Also at Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, USA.

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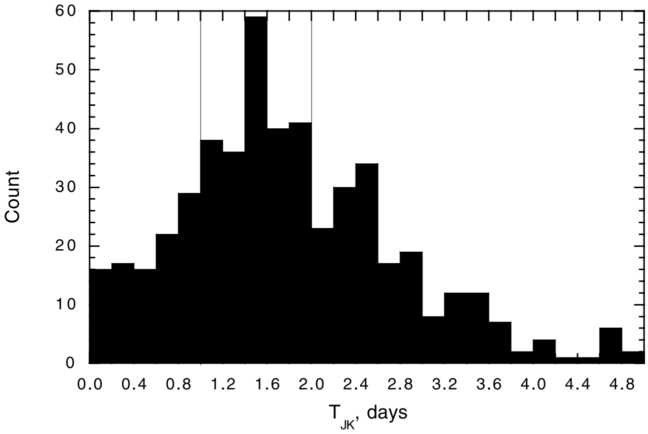

Figure 1. Frequency of occurrence of the period T_{JK} that separates quasi-static structures in the solar wind from the shorter period fluctuations. Vertical lines are drawn at 1 and 2 days.

of 1-min and 1-hour data. The hourly data over 1-day intervals covers the range of principal interest for this study. The 1-hour lower limit approximately corresponds to the breakpoint in power spectra of the polar magnetic field from a slope of $f^{-5/3}$ indicative of the turbulent range to a slope of f^{-1} at lower frequencies (f) (see Figure 4.9 of *Horbury and Tsurutani* [2001]). The 1-day upper limit was chosen on the basis of Figure 1 which shows the occurrence rate of the period T_{JK} predicted to divide quasistatic or structural variations from wave variations [*Heinemann and Olbert*, 1980; *Jokipii and Kóta*, 1989].

$$T_{JK} = 4\pi r V_{AR}/V_{SW}^2 \tag{1}$$

where r is distance from the Sun, V_{AR} is the radial projection of a field-aligned Alfvén velocity, and V_{SW} is the solar wind speed. Each value of T_{JK} in Figure 1 was calculated from 12-hour averages of the included parameters for periods when Ulysses was poleward of ±30° latitude during the first

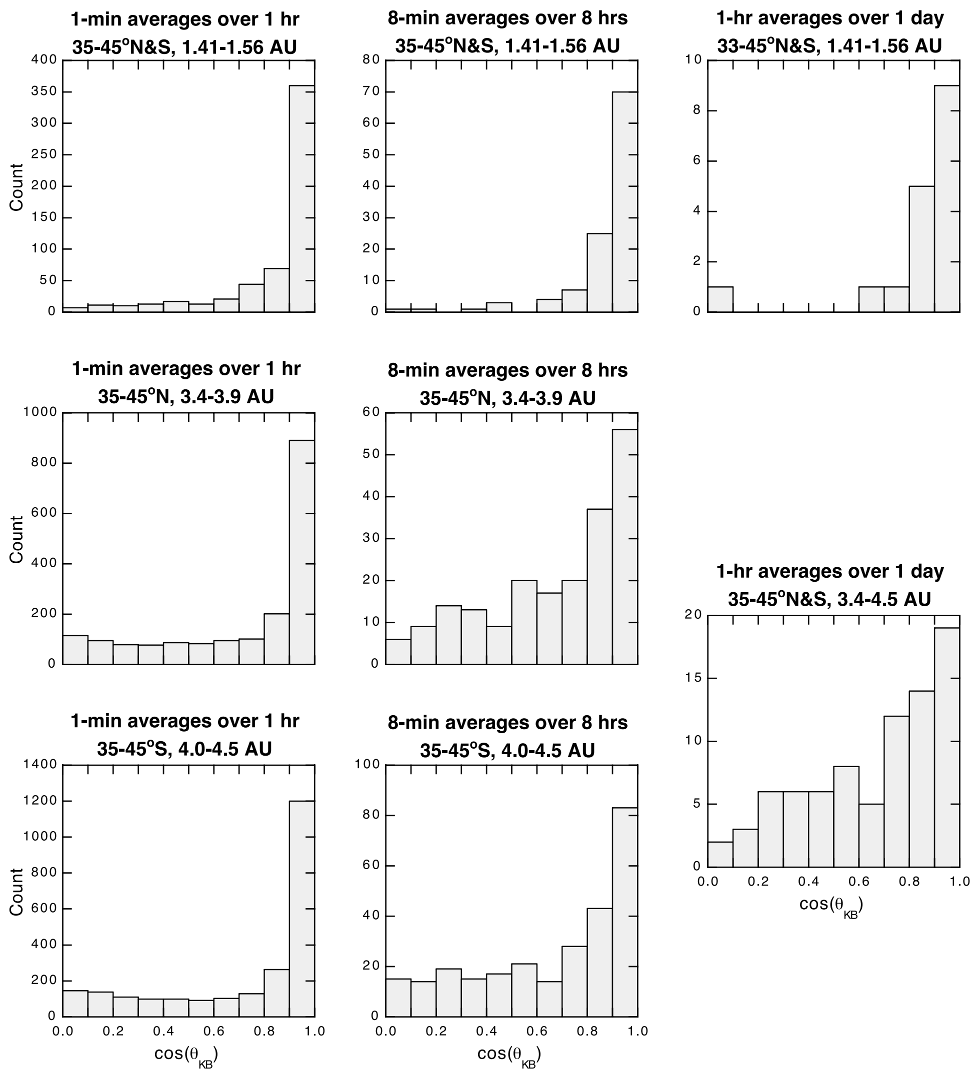

Figure 2. Distributions of the cosine of the angle θ_{KB} between the minimum variance direction and the magnetic field. Time scale increases to the right and solar distance increases from top to bottom.

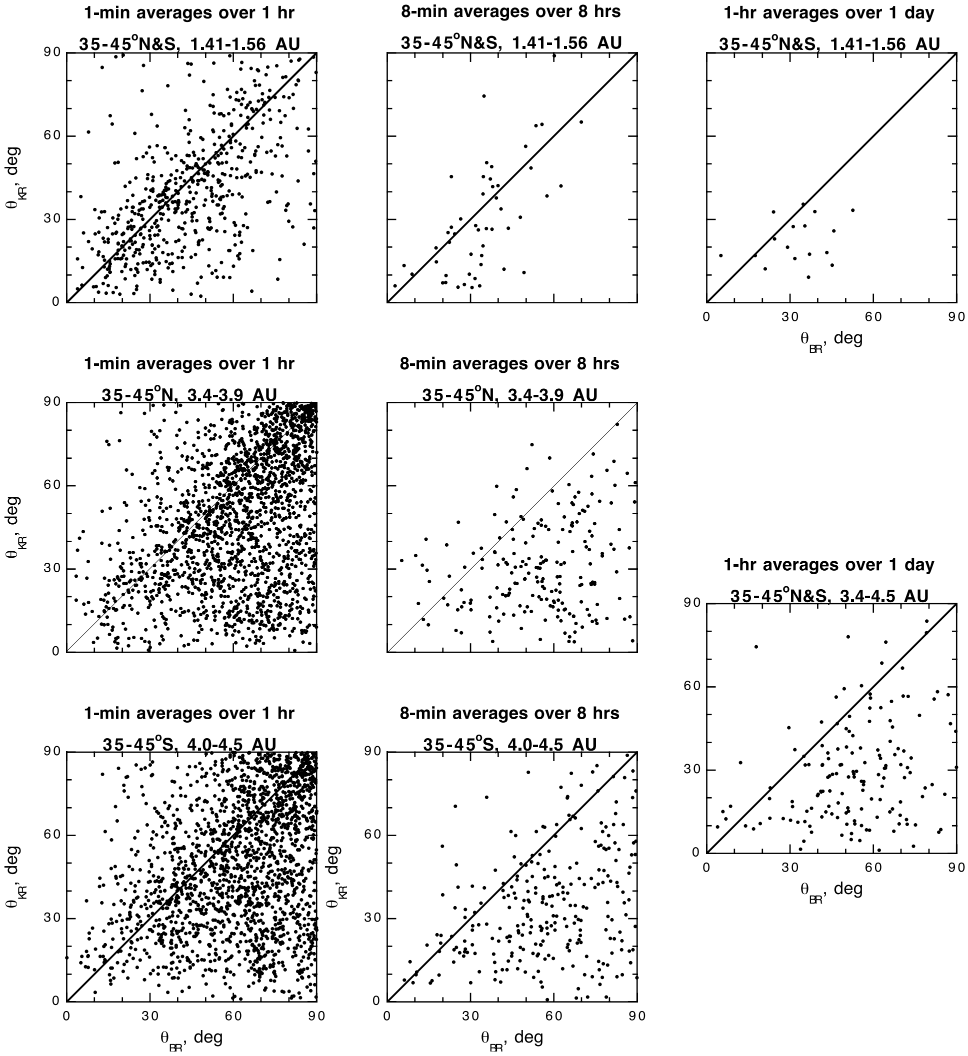

Figure 3. Scatter diagrams of the angle θ_{KR} between the minimum variance direction and the solar radius direction versus the angle θ_{BR} between the magnetic field and the radial direction. Time scale increases to the right and solar distance increases from top to bottom.

Ulysses solar orbit and for which the speed V_{SW} exceeded 650 km/s.

[6] The principal-axis analysis [*Sonnerup and Cahill*, 1967] calculates the eigenvalues and eigenvectors of the covariance matrix M_{ij}, given by

$$M_{ij} = \langle B_i B_j \rangle - \langle B_i \rangle \langle B_j \rangle \qquad (2)$$

where the brackets denote averages and the B_i or B_j denote RTN components of the magnetic field vector. The eigenvalues λ_1 and λ_3 are the variances along the axes of maximum and minimum variance, respectively, while λ_2 is the intermediate variance along the third, orthogonal axis. The ratio λ_1/λ_3 is a measure of the anisotropy of the variations. The ratio λ_2/λ_3 is a measure of the planarity (transverseness) of the variations, and $\lambda_2/\lambda_3 = 2$ is often considered to be a minimum value for meaningful determination of the principal axes [*Lepping and Behannon*, 1980]. The original vectors can be rotated into the principal axis coordinate system with the normals to planar discontinuities and the assumed direction of propagation of transverse waves being along the minimum variance direction (axis 3).

[7] The first step of the analysis is based on data obtained in the heliographic latitude ranges of ±(35–45°). That latitude range was used instead of some higher-latitude range because the spacecraft spent more time and obtained more data at the lower latitudes. The spacecraft crossed the ±(35–45°) band four times during its first orbit, at radial distances of 4.49 to 4.00 AU (days 207 to 327, 1993), 1.56 to 1.50 AU (days 363, 1994, to 13, 1995), 1.41 to 1.46 AU (days 109–122, 1995) and 3.42 to 3.90 AU (days 62 to 157, 1996). Within those boundaries, each component of the field and velocity vectors was detrended over intervals of 1 hour, 8 hours, and 1 day by subtraction of a linear least-squares fit versus time; this focuses the analysis on waves and other short period fluctuations in preference to solar wind structures such as microstreams. For each 1-hour, 8-hour, and 1-day interval, the principal axes of the detrended magnetic field data were then calculated and both the field and velocity data were rotated into the principal axis coordinate system. For most of the further analyses, intervals for which

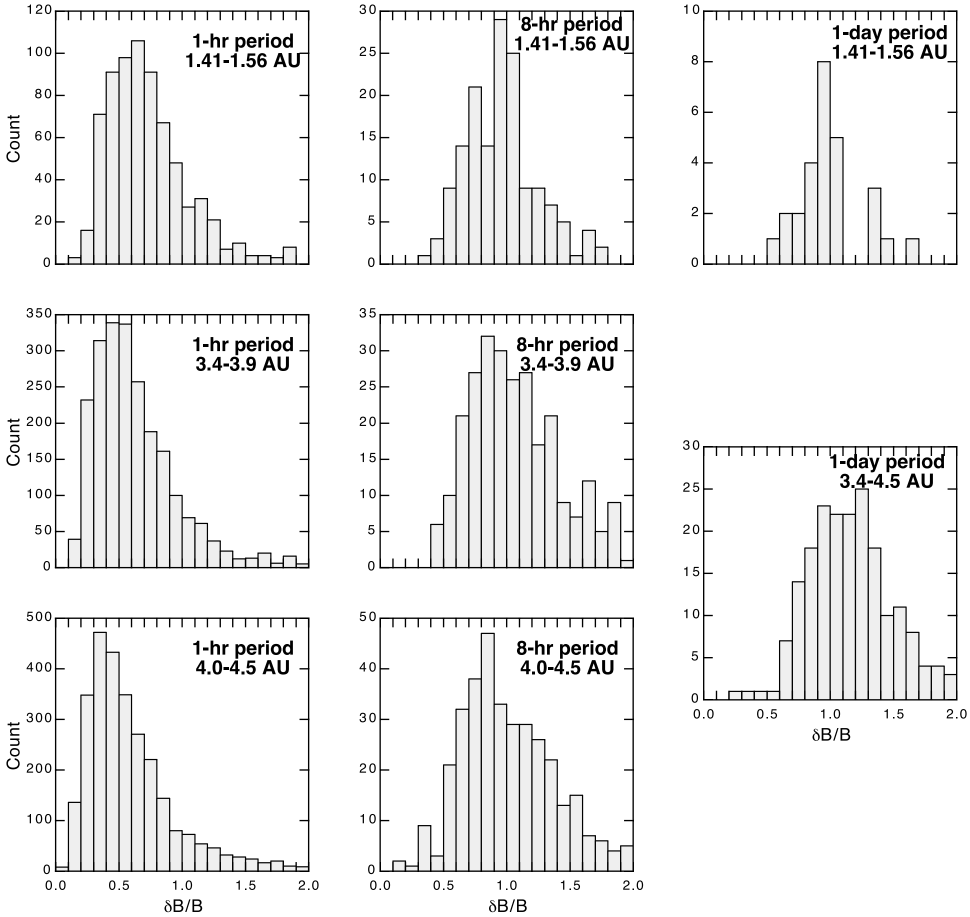

Figure 4. Frequency of occurrence of the variation in the components of the magnetic field relative to the field magnitude as a function of time scale and solar distance.

the ratio of the medium to the minimum eigenvalues λ_2/λ_3 was <2.0 were edited out of the data set. Finally, the correlation between the field and velocity was found for each axis for each remaining interval.

3. Results

[8] Figure 2 shows the distributions of the cosine of the angle θ_{KB} between the minimum variance direction (the **k** vector) and the magnetic field **B** for the times Ulysses spent in the $\pm(35-45°)$ latitude range. The statistical significance of the fast-latitude data set has been increased by combining the data for the Southern and Northern Hemispheres; even then the number of samples of 1-day intervals is still regrettably small. The southern and northern data at the greater solar distances have similarly been combined for the analysis of 1-day intervals. In Figure 2 the interval duration increases to the right, while the solar distance increases down the page. As expected on the basis of earlier work [e.g., *Horbury et al.*, 1995], the fluctuations at the shortest periods (inertial turbulence range) are usually closely aligned with the magnetic field with $\cos\theta_{KB} > 0.9$. The alignment degrades with increasing period and with increasing distance from the Sun.

[9] Some further insight into the direction of the anisotropy of the fluctuations can be gained from the scatter plots in Figure 3. In each diagram the angle θ_{BR} between the field **B** and the radial direction is plotted on the abscissa and the angle θ_{KR} between the minimum variance direction **k** and the radial direction is plotted on the ordinate. If **k** is aligned with **B**, the points will fall on the diagonal line. In the top row, corresponding to the smaller distances from the Sun, the points are scattered about that line, with a slight tendency for greater deviation from the line with increasing period. There is also a slight preference for the points to fall below the line, indicating **k** more radial than **B**, rather than above it. The lower rows present quite different pictures. In the lower left panels, many points are still close to the line and they are concentrated in the upper right corner, reflecting the fact that the spiral angle is more tightly wound at these greater distances. Even for the short-period fluctuations, however, there are many more points below the line than above it. At longer periods, that tendency is more pronounced, and for 1-day intervals nearly all the **k** vectors are more radial than the field.

[10] The next three figures show the dependences of other properties of the fluctuations as functions of period and solar distance in the same format as Figure 2. Figure 4 shows distributions of the relative amplitudes of the fluctuations. It is well known that both the variance and the magnitude of the magnetic field decline with increasing distance from the Sun. Figure 4 shows $\delta B/B$, where δB is the square root of the sum of the variances along the three axes and B is the average magnitude of the field. Note that

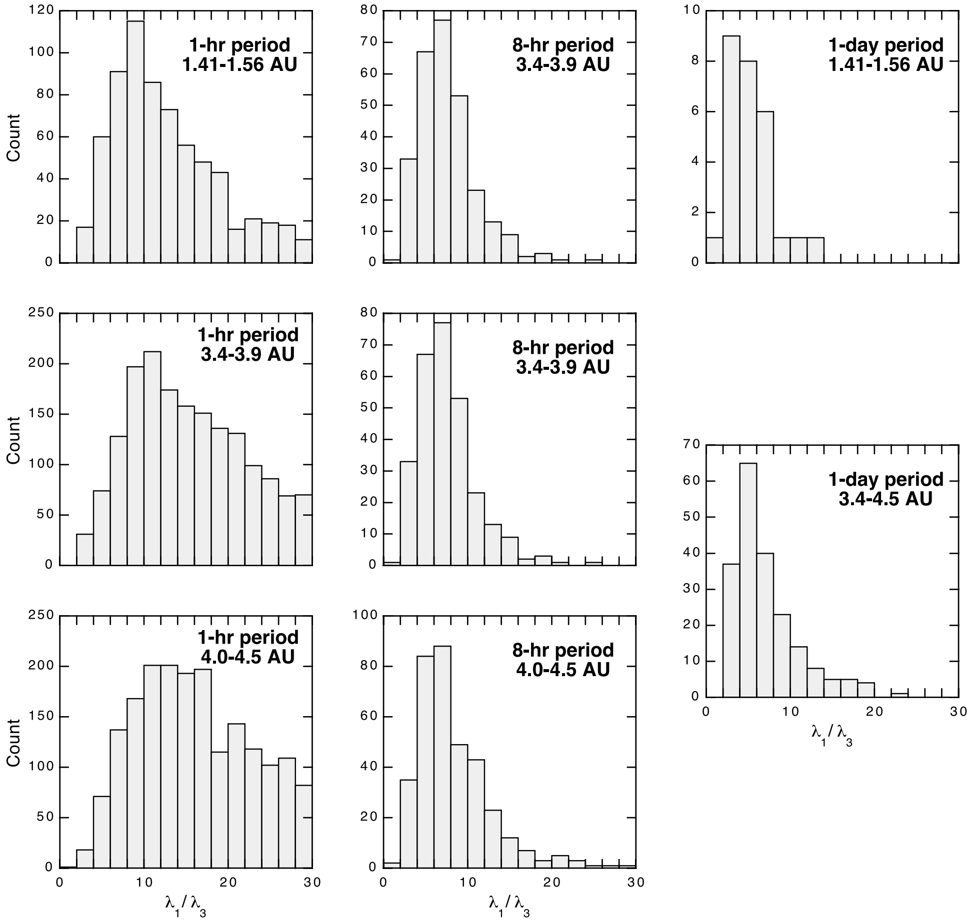

Figure 5. Frequency of occurrence of the ratio of the variances along the maximum and minimum variance axes as a function of time scale and solar distance.

δB includes only the fluctuations remaining after the data had been detrended for slow variations. At both distance ranges, $\delta B/B$ increases with increasing period, more than doubling between the 1-hour data and the 1-day data. In the inertial range (1-min data over an hour), the value of $\delta B/B$ decreases with increasing distance, whereas for the longest period data, $\delta B/B$ increases slightly with distance.

[11] The change in anisotropy as measured by the eigenvalue ratio λ_1/λ_3 is shown in Figure 5. Anisotropy becomes smaller at longer periods and greater at larger distances. The increase in anisotropy with distance is especially noticeable in the enhancement of the high-anisotropy tails to the distributions.

[12] Figure 6 presents the distributions of the ratio λ_2/λ_3 which is a measure of both the reliability of the determination of the minimum variance direction and the transverseness or two-dimensionality of the fluctuations. Overall, the distribution of λ_2/λ_3 changes very little with either period or distance.

[13] Correlations of the fluctuations in the field **B** and velocity **V** are investigated using hourly averages of the vector components accumulated over 24 hours. Figure 7 presents the radial dependence of the B_i-V_i correlation coefficients for i = 1, 2, 3 for all daily intervals poleward of ±35° for which λ_2/λ_3 exceeded 2.0. Any dependence on latitude is ignored in this presentation. Ulysses reached peak latitudes of ±80° at a radial distance of 2.3 (2.0) AU in the southern (northern) hemisphere, and the scatter plots in Figure 7 show very little structure centered at those distances. This predominance of radial over latitude variations was also found by *Goldstein et al.* [1995] and *Bavassano et al.* [2002]. It is seen in Figure 7 that the Alfvénicity, as indicated by B-V correlations, decreased with distance. In the top and middle panels, in the plane transverse to **k**, the envelope of the maximum values of the correlations slowly declined, and the fraction of intervals with low correlation increased with distance. Beyond about 4.2 AU, the fluctuations along the minimum and intermediate variance axes were not, on the average, appreciably more Alfvénic than those along the minimum variance direction. These results are consistent with those found earlier for the correlations of hourly averages of B_N-V_N and B_T-V_T over entire solar rotations [*Smith et al.*, 1995; *Neugebauer*, 2001], although the way the data were plotted by Smith et al. misleadingly suggested a latitudinal rather than a radial variation.

[14] Figures 8 and 9 are plots of the field and velocity components in the eigenvector coordinate system for two of the days included in Figure 7. The data in Figure 8 were obtained on days 138–139, 1995 at a solar distance of 1.54 AU and a heliographic latitude of 54.7°N. For that interval, the ratio λ_2/λ_3 = 2.8, the angle θ_{KB} = 15° (**k** is nearly aligned with **B**) and the angle θ_{KR} = 5° (both **k** and **B**

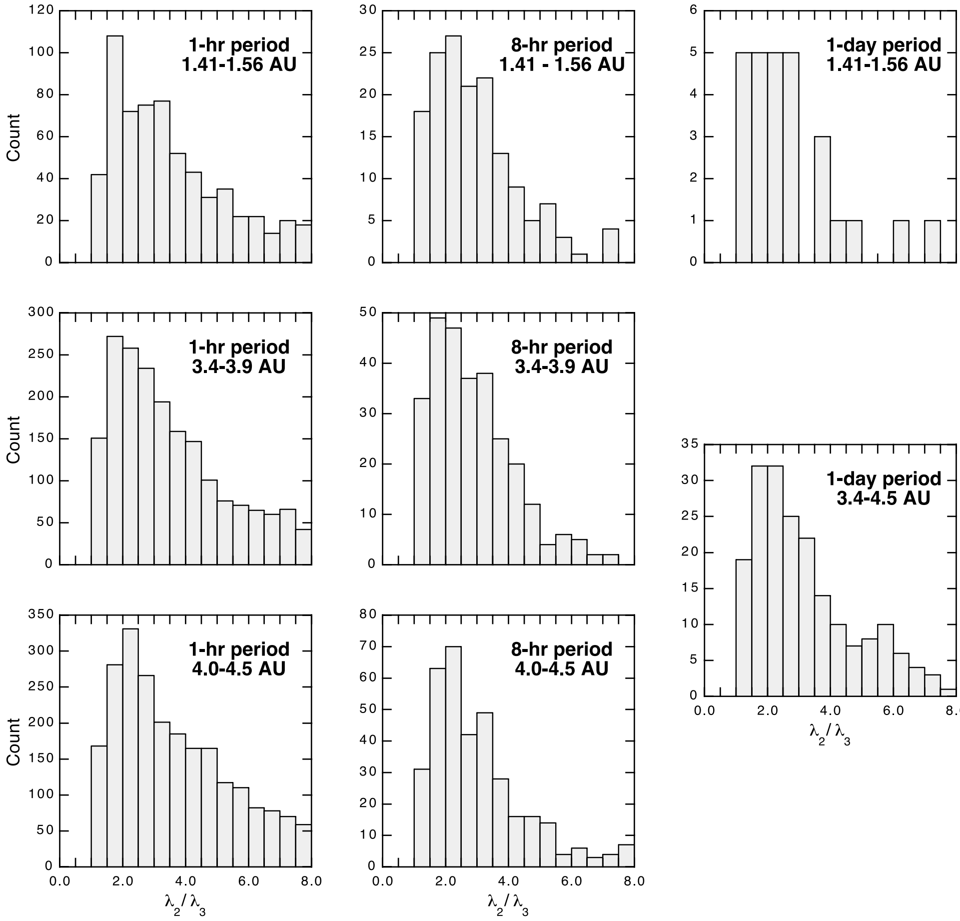

Figure 6. Frequency of occurrence of the ratio of the variances along the intermediate and minimum variance axes as a function of time scale and solar distance.

are quasi-radial). The heavy lines with circles are plots of the magnetic field whose scale is on the left. The velocity components are indicated by the thin lines with crosses and by the scale on the right. The components in the maximum, intermediate, and minimum variance directions are displayed from top to bottom, respectively, with each panel drawn to the same scale. Note that the velocity scale has been inverted so that the field and velocity fluctuations would be in phase for outward propagating Alfvén waves. In fact, the field and velocity fluctuations in the plane perpendicular to the minimum variance direction track each other very closely with correlation coefficients $R_1 = 0.95$ and $R_2 = 0.90$. This is the behavior expected for Alfvén waves. An ideal, small amplitude Alfvén wave would have no B-V correlation along the direction of minimum variance, but in this case $R_3 = 0.55$. This could be explained by a temporal change in the direction of the underlying field along which the waves were propagating. For an ideal Alfvén wave, there should also be no variation of the field magnitude; for this day, $\sigma_{|B|}/B = 0.026$, where $\sigma_{|B|}$ is the standard deviation of the variations in the magnitude of the magnetic field before the data were detrended.

[15] Figure 9 presents similar plots for a 24-hour interval on days 117–118, 1996, at a solar distance of 3.71 AU and a latitude of 38.8°N. For this interval, the ratio $\lambda_2/\lambda_3 = 3.2$, the angle $\theta_{KB} = 78°$ (**k** is nearly perpendicular to **B**), and the

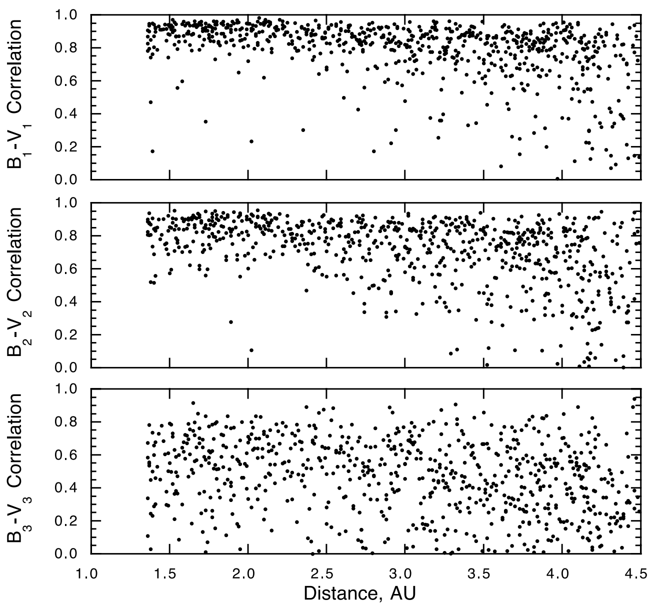

Figure 7. Correlation coefficients for the magnetic field and velocity components in the eigenvector coordinate system as a function of distance from the Sun.

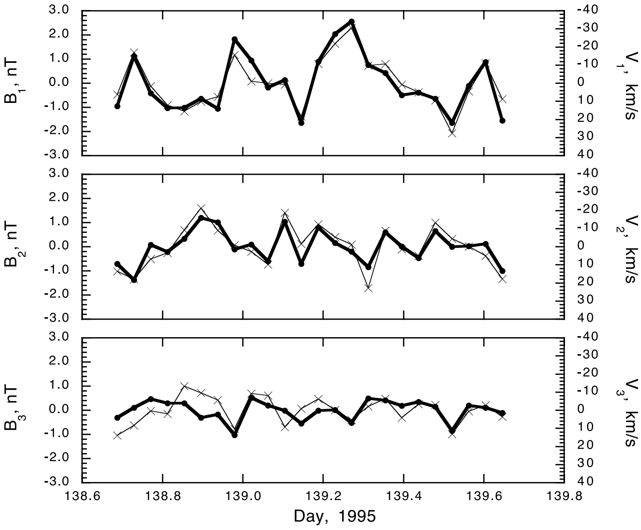

Figure 8. Plots of the components of the magnetic field and velocity in the eigenvector coordinate system for 24 hours of data obtained at 1.54 AU. The magnetic data are represented by the heavy lines whose scale is on the left and the velocity data are represented by the thin lines whose scale is on the right.

angle θ_{KR} = 23° (the minimum variance direction **k** is quasi-radial). Here the correlation coefficients between the field and velocity components along the three eigenvector axes were R_1 = 0.76, R_2 = 0.51, and R_3 = 0.55. The maximum variance axis appears to have been determined on the basis of the two large discontinuities at days ~118.25 and ~118.45. Higher-resolution data confirms these features to be discontinuities. Thus for this day, the V-B correlations were roughly equal on all three axes, in contrast to R_3 being significantly less than R_1 and R_2 for the interval shown in Figure 8.

[16] Coincident with the radial decrease in V-B correlations and the increasing change in the direction of **k** from field-aligned to radial, the relative variation in field magnitude $\sigma_{|B|}/B$ has also been found to increase with both radial distance and period [*Horbury and Balogh*, 2001]. Extensions of the present analysis agree with those conclusions and additional plots to confirm the earlier work are not presented here.

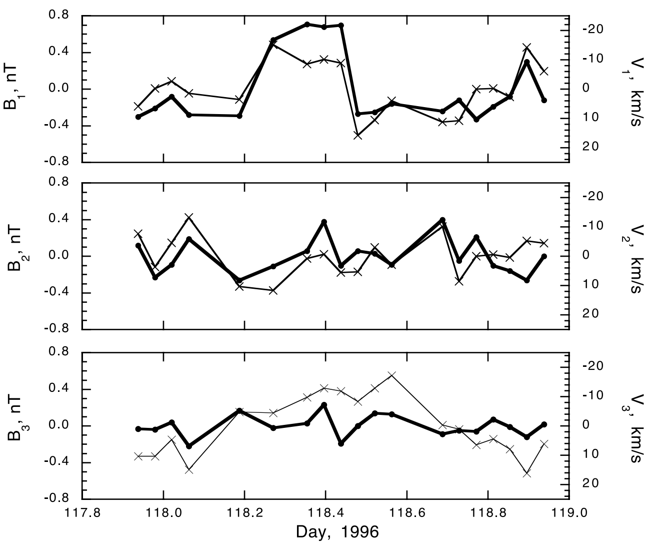

Figure 9. Same as Figure 8 for 24 hours of data obtained at 3.71 AU.

Table 1. Dependences of Several Properties of Fluctuations in the Magnetic Field Determined From This Analysis[a]

Parameter	As Distance Increases	As Period Increases
Alignment of **k** with **B**	▼	▼
Alignment of **k** with **R**	▲	▲
λ_1/λ_3 (Anisotropy)	▲	▼
λ_2/λ_3 (Transverseness)	•	•
$\delta B/B$ (Components) - @ 1 and 8 hours	▼	▲
@ 1 day	▲	▲
$\sigma_{|B|}/B$ (Magnitude)	▲	▲
V_1-B_1 and V_2-B_2 Correlations	▼	
V_3-B_3 Correlation	•	
PMS frequency	▲	

[a]Upward triangles represent increases, downward triangles represent decreases, and circles represent no significant dependence.

4. Discussion

[17] Table 1 presents a summary of the dependences of the magnetic and velocity fluctuations on period and distance as determined from Figures 2–7 and by *Horbury and Balogh* [2001]. These results must be interpreted in the context of similar findings at other latitudes and frequencies. A good review of the in-ecliptic observations has been given by *Tu and Marsch* [1995], while *Horbury and Tsurutani* [2001] have summarized previous high-latitude studies.

[18] As both the period and the distance from the Sun increase, the high-latitude minimum variance direction **k** becomes less aligned with the field direction and more closely aligned with the radius vector from the Sun. The radial dependence of the spread of the magnetic minimum variance direction about the field direction was observed in high-speed streams in the ecliptic in both the Helios (0.3–1.0 AU) [*Klein et al.*, 1993] and Voyager (1 to 10 AU) [*Klein et al.*, 1991] data. This similarity is despite the fact that the time resolution of both of the in-ecliptic studies corresponded to the inertial range, whereas the right-hand columns of Figures 2 and 3 correspond to longer periods. The increase in scatter with period may be caused by slow variations in the direction of the field along which the waves are propagating. The approach of the minimum variance direction to the radial is discussed further below.

[19] The anisotropy, as measured by λ_1/λ_3, decreases at longer duration intervals but increases with greater radial distance. The cause of the dependence on period may be similar to that discussed above for the increase in scatter of the minimum variance direction about **B**; that is, the underlying field may change direction during the interval being analyzed. A similar effect has been seen in the ecliptic [*Bavassano et al.*, 1982; *Klein et al.*, 1991]. *Klein et al.* [1991] suggest that for periods >12 hours, structures such as corotating interaction regions or coronal mass ejection plasma may play a role. In the ecliptic, reports on the dependence of anisotropy on solar distance are mixed; *Marsch and Tu* [1990] and *Klein et al.* [1991] found a

decrease of anisotropy with increasing distance, whereas *Bavassano et al.* [1982] found the opposite. Figure 5 shows that the increase in the average anisotropy with solar distance is largely, but not entirely, associated with a significant increase in the high-anisotropy tail of the distribution. This is in accord with the reanalysis of Helios data by *Bruno et al* [1999]; when the whole distribution is taken into account, the anisotropy increases with distance, whereas if the high-energy tail due to the intermittency of the wave population is removed, the anisotropy is approximately constant between 0.3 and 1.0 AU. That may be what is seen in the Ulysses data shown in Figure 5. The distribution of the ratio λ_2/λ_3, which is a measure of the transverseness or planarity of the magnetic fluctuations, does not appear to depend strongly on either period or distance.

[20] As measured by the correlation between the field and velocity components in the plane perpendicular to the minimum variance direction, the Alfvénicity of the fluctuations decreases with increasing solar distance. The correlation along the minimum variance direction is quite scattered, but averages $\sim$0.5 at all distances in the fast high-latitude wind. This radial dependence of V-B correlations over daily intervals is quite different from that determined by *Bavassano et al.* [2000] for Ulysses data over hourly intervals (in the inertial range). They found the hourly V-B correlation to decrease with distance out to $\sim$2 AU and then to remain at a constant value of $\sim$0.5 at greater distances. Finally, the relative amplitudes of the fluctuations in the detrended field components increase with period but are relatively independent of distance, while the relative amplitudes of the fluctuations in the field magnitude increase with both distance and period.

[21] What is going on? In most respects, the temporal and radial trends of the anisotropy of magnetic fluctuations in the polar solar wind are similar to those observed in the high-speed wind in the ecliptic, despite the absence of major stream interactions and strong shear flows. It is clear that for periods of a day, for which turbulent cascading is thought to be absent, the minimum variance direction is determined by something other than transverse Alfvén waves and that the discrepancy with such waves increases with distance from the Sun. The increase in anisotropy with distance is opposite to the increasing isotropy predicted by *Roberts* [1990]. The data in Figure 9 suggest that discontinuities may play a role. According to *Tsurutani et al.* [1996], the observed rate of occurrence of interplanetary discontinuities in the fast polar solar wind was nearly independent of distance, but the thickness of those discontinuities increased with distance with a consequent decline in their detectability by the methods used.

[22] Perhaps more relevant is the observation of planar magnetic structures (PMS) in the high-latitude wind reported by *Jones and Balogh* [2000]. They defined a PMS as a period of at least 6 hours during which the interplanetary field experiences large changes of direction, often discontinuously, while remaining within a single plane. Figure 9 of the paper by *Jones and Balogh* [2000] shows a strong clustering of the PMS normals toward the radial direction. Furthermore, Figure 1 of another paper by *Jones and Balogh* [2001] demonstrates that when Ulysses was in the fast polar solar wind the rates at which PMS were encountered increased with distance. The maximum 40-day-average rate for the interval considered in the present study (mid-1993 to late 1996) was $\sim$0.6 PMS per AU. At an average wind speed of 750 km/s, that corresponds to $\sim$0.3 PMS per day, which is about the frequency needed for consistency with the results in this paper.

[23] It has been suggested that PMS are caused by compressional alignment of preexisting structures such as discontinuities [*Neugebauer et al.*, 1993; *Jones and Balogh*, 2000]. Of the 667 Ulysses PMS studied by *Jones and Balogh* [2000], all but 255 were associated with shocks, corotating interaction regions, or the heliospheric current sheet. With the exception of a very few shocks, none of those phenomena were present in the high-latitude data studied here. Although the fast polar solar wind does exhibit some compressions associated with features called microstreams [*Neugebauer et al.*, 1995], the compressions are not as large as those seen at lower latitudes, and it is not known whether or not the PMS studied by Jones and Balogh were preferentially found on the leading edges of the microstreams. An alternative to the one-dimensional compression usually associated with PMS is expansion in the other two dimensions as the solar wind from coronal holes expands to fill all space. The departure of the minimum variance direction from field alignment to a more radial direction found in the present study and the approximately radial orientation of the normals to the PMS studied by *Jones and Balogh* [2000] may both be a manifestation of the randomly oriented transverse fields predicted to dominate the polar heliosphere by *Jokipii and Kóta* [1989].

[24] It should also be noted that equation (1) was never intended to provide an exact prediction of the period at which quasi-static structures (e.g., tangential discontinuities) become more important than Alfvén waves. The present results suggest that the quasi-static regime may, at times, come close to or even overlap the turbulent inertial regime.

[25] A final comment is in order concerning the principal axis technique used here. *Knetter et al.* [2003] have recently compared the normals to discontinuities calculated from the times when structures passed each of the four Cluster spacecraft to the normals determined by principal axis analysis. They found close agreement between the two sets of normals only for those few discontinuities for which the eigenvalue ratio λ_2/λ_3 exceeded a value of 10. They concluded that wave fields in the vicinity of a discontinuity could often prevent valid determination of discontinuity normals. The present paper reaches a complementary conclusion: discontinuities can often prevent a valid determination of the direction of propagation of waves. The principal axis technique responds to whatever is present and nature seldom presents us with isolated structures or wave trains.

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M. Neugebauer, Lunar and Planetary Laboratory, University of Arizona, 1629 E. University Blvd., Tucson, AZ 85721, USA (mneugeb@lpl.arizona.edu)